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ORIGINAL PAPERS

ASSESSMENT OF RENATURATION IN ACTIVE AND INACTIVE QUARRIES USING REMOTE SENSING DATA

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Abstract. *Surface mining, crucial for supplying raw materials, alters topography, habitat structures, and vegetation cover. Monitoring environmental quality in quarries is complex due to extensive affected areas, cost and time constraints. Vegetation quality and dynamics are often used as crucial indicators for monitoring environmental quality and renaturation. Using remote sensing technologies, the Normalized Difference Vegetation Index (NDVI) is a reliable index for tracking changes in vegetation. We compared active and inactive quarries using NDVI data and climate parameters from the last 10 years in active quarries and for almost three decades (since inactivation) in inactive quarries. NDVI values increased over time in both active and inactive quarries. Quarries surrounded by forest habitats have higher NDVI values overall, but also in only inactive quarries when compared to active quarries. However, quarries surrounded by open mixed habitats (agricultural and steppe lands) have a significantly lower NDVI in almost all instances. Only when comparing active to inactive quarries, NDVI is significantly higher in present moment in inactive quarries. Climate parameters are at most low correlated with NDVI trends. NDVI is low correlated with minimum temperature and direct solar radiation (DSR) in active quarries, while in inactive quarries with precipitation and DSR. This study highlights the importance and efficiency of using NDVI in quarry renaturation monitoring and analysis. Additionally, we consider this study to be a starting point for studies supporting the necessity for biodiversity management measures taken to support quarries' renaturation.*

Keywords: satellite images, ecological monitoring, natural vegetation succession, environment quality trends, indicators

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Introduction

Surface mining is an important industry that provides essential raw materials used in the majority of infrastructure and construction development

projects. However, its effects on biodiversity are immediate and long-lasting. Excavations significantly alter topography and modify habitat structures. Heavy machinery and procedures for extraction, transportation, and processing procedures for resources and waste materials further affect biodiversity by altering soil properties, vegetation cover, and producing atmospheric, sound, and light pollution [3, 5, 18, 19, 37, 51, 54].

When extraction and excavation in surface quarries is ended, the altered space creates new habitats, giving biodiversity a chance to recolonise with both initial species as well as new ones taking advantage of the new habitats [14, 18, 47]. Unfortunately, natural, passive reclamation of inactive quarries can be slow, with successive stages of revegetation needing time to successfully establish. This can be further slowed down by the level of degradation and the features of the surrounding landscape [3, 25, 54]. Active renaturation—artificially applying specific, active technical and biological steps towards renaturation and improving general environmental quality—can promote faster renaturation of surface quarries [3, 4, 18, 25, 54]. The decision between passive and active renaturation depends on financial and temporal resources, as well as efficient and clear end results of each process [25, 54]. In the context of present-day environmental issues–climate change, continued habitat quality degradation, habitat fragmentation–ecosystem restoration, in this specific case, quarries renaturation, is a clear necessity [4, 18, 25]. More so, renatured inactive quarries can even further be used for scientific and educational purposes [42, 43], as well as included in ecotourism strategies [9, 12].

As such, understanding and monitoring the environmental impact of active quarries as well as renaturation processes in inactive quarries is important. The mapping of surface activities and environmental assessments is complex due to extensive affected areas, and the monitoring and management of changes are further complicated due to cost and time constraints [52]. Geographic Information System (GIS) and remote sensing technologies provide essential data for assessing and monitoring changes in environmental quality and ecological restoration, allowing scientists to monitor vegetation cover, restore degraded areas, and examine the long-term impacts of ecological engineering [52, 53]. A crucial indicator for such an endeavor is vegetation; indexes based on vegetation offering a scientific foundation for evaluating and monitoring environmental quality, restoration outcomes, and developing future management plans on a local, regional, and global scale [53]. The Normalized Difference Vegetation Index (NDVI) is a reliable satellite-derived vegetation index used to detect vegetation quality and dynamics [13, 23, 29, 56]. NDVI is used and applied in agriculture land resources management [20, 48], in wildlife management of herbivores [28], and in environmental impact assessment studies [2, 3, 52, 55]. This index analyses

the difference between near-infrared light, which is reflected by vegetation, and the red light, which is absorbed by vegetation [2]. Vegetation productivity is affected by variation in temperature, precipitation, and solar radiation [11, 34].

While there studies involving the remote sensing data to analyse the plant communities in quarries [3, 26, 36, 57], none of them compared the NDVI mean values between active and inactive quarries.

In this study, our goal was to assess the use of NDVI in analysing and monitoring surface quarry renaturation processes. We accomplished this by comparing the observed changes in vegetation condition over time in active and inactive quarries (1) and taking into account surrounding habitats (2). Additionally, we checked for climatic parameters influence on NDVI trends over time (3).

Material and methods

Study area

Dobrogea is a south-eastern region in Romania, bordered by the Black Sea, the last part of the lower basin of the Danube, and the Danube Delta. Dobrogea represents 4.3% of Romania's territory [7] divided into three morphogeologic regions: the Northern, the Central, and the Southern Dobrogea Plateau [7, 32, 41]. Northern Dobrogea is characterised by its diverse topography, where the substrate is mainly formed by hard rocks, including quartz, magnetite, and crystalline schists [40]. Central and Southern Dobrogea regions are characterised by homogenic topography with low elevations. The substrate in Central Dobrogea is composed mainly of greenschists [39] while in Southern Dobrogea is composed mainly of limestone and gneisses [1]. In Dobrogea the climate is continental, dry with mediterranean and subtropical influences [49]. This region receives the most solar radiation in Romania, with annual averages of sunlight often over 2000 hours (approx. 50% of the annual astronomical possibility of sunlight in the area) [6]. Vegetation is diverse but specific to such conditions, with three main distinct natural landscapes: steppe, forest–steppe, and broad-leaf forest [22, 41].

We selected six surface quarries from Dobrogea, three active (sandstone and limestone) and three inactive quarries (granite, limestone, and diatomite) (Table 1, Fig. 1). We selected these quarries based on 1) available information about their activity and 2) surrounding habitats.

The surrounding habitats were categorised in: forest found in 2 quarries (CF and B) and open mixed habitats—steppic and agricultural fields—found in 4 quarries (BR, NB, S, and U). The steppic habitats are usually used as grazing grounds by local farmers. Artificial renaturation steps have been taken in none of

the inactive quarries to our knowledge and after discussion with the local community.

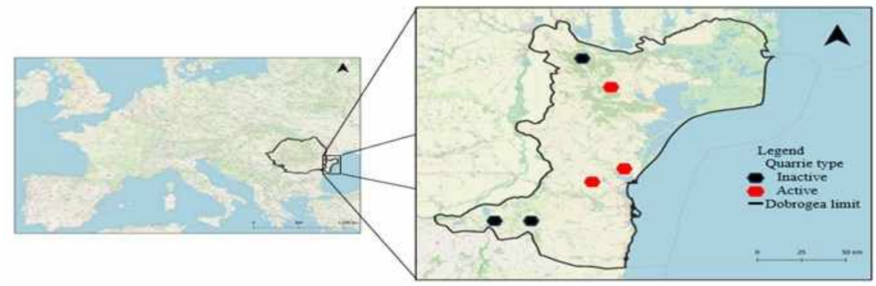

Fig. 1. Locations of the inactive and active quarries across Dobrogea

Table 1. Analysed quarries description

Quarry code	*Dobrogea region*	*Surface (ha)*	*Extracted material*	*Surrounding habitat*	*Data range*	*Status*
BR	Northern	4.2	Granite	Open mixed	1996–2024	Inactive
CF	Southern	7.52	Limestone	Forest	1990–2024	Inactive
U	Southern	37.89	Diatomite	Open mixed	1996–2024	Inactive
B	Northern	6.89	Sandstone	Forest	2014–2024	Active
NB	Central	97.08	Limestone	Open mixed	2014–2024	Active
S	Central	31.46	Limestone	Open mixed	2014–2024	Active

NDVI and climate data

NDVI (Normalized Difference Vegetation Index) is a remote sensing index that assesses vegetation health and density. It is calculated using satellite or aerial imagery by measuring the difference between the light reflected by vegetation and the light absorbed by vegetation (Meneses-Tovar, 2011). We used NDVI to assess how plant communities recolonise quarries. The formula for NDVI is as follows:

$$NDVI = (NIR - RED) / (NIR + RED),$$

where RED is the proportion of red light in the electromagnetic spectrum (0.6–0.7 μm) and NIR is the proportion of near-infrared light in the electromagnetic spectrum (0.75–1.5 μm) [3, 52].

NDVI values range from −1 to +1, where values close to +1 indicate healthy, dense vegetation, values close to 0 indicate sparse or no vegetation, and values close to −1 typically correspond to water, clouds, or snow [28].

We obtained NDVI data from the ClimateEngine online on-demand data [16], which uses datasets acquired by Landsat 5/7/8/9 SR (surface reflectance) sensors owned by NASA/USGS. We overlaid the quarries limit over the aerial images, and these datasets provided NDVI values from a 30 m pixel grid system. We used the mean values of these pixels and obtained data for the past ten years (in the case of active quarries) and since the closure time up to the present (for inactive quarries). To see how mean NDVI changes between groups (type of quarry and surrounding habitats) in time, we chose to define two moments of two years each in the dataset: initial moment (A) and present moment (B). The initial moment is represented by the first two years in each quarry's data set: 2014 and 2015 for active quarries and the first two years of inactivity for inactive quarries.

Moreover, we overlaid the same quarries limit over the aerial images and downloaded climate data for the same period (mean, minimum and maximum temperature, precipitation (PPT), and downward shortwave radiation (DSR)). This data was used to find if there is any correlation between NDVI and climatic parameters in order to see if there is any other underlying possible effect to explain the NDVI difference in active and inactive quarries and between initial and present moments. We used the AgERA5 dataset at a spatial resolution of 9600 m, which consists of daily surface meteorological data owned by the European Centre for Medium-Range Weather Forecasts The climate data is derived from gridded observational datasets (0.1° x 0.1°) [10].

Statistical analysis

We applied the Shapiro-Wilk test for normality on all data sets. Because our data has an asymmetric distribution, we further used the Mann-Whitney U test to analyse variation in mean NDVI values between 1) type of quarry; 2) temporal scale (initial and present moments); and 3) surrounding habitats. For correlations between NDVI and climatic parameters, we performed Székely-Rizzo-Bakirov Distance Correlation analysis [45]. Values of the correlation range from 1 (strong positive correlation) to −1 (strong negative correlation). Values (positive or negative) ranging from 0 to 0.2 represent insignificant correlation, from 0.2 to 0.4 low correlation, 0.4 to 0.6 medium correlation, 0.6 to 0.8 strong correlation, and 0.8 to 1 high correlation. Moreover, we computed the tendency of the NDVI and the annual mean of climatic parameters. We performed all the statistical analysis using IBM SPSS Statistics [58].

Results

The average annual values of the NDVI showed an increase in the values for both active quarries (2014–2024) and inactive quarries (1990–2024). In the case of active quarries, the lowest mean value of NDVI was observed in 2015 (0.231) and the highest in 2024 (0.299). In the case of inactive quarries, the lowest mean value of NDVI was observed in 2001 (0.256) and the highest in 2024 (0.441) (Fig. 2).

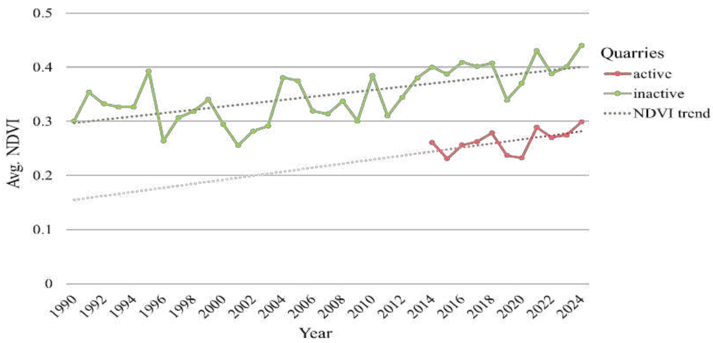

Fig. 2. Mean NDVI in active and inactive quarries over time

Our results show that the mean values of NDVI have no significant differences between active and inactive quarries in the initial moment ($Z = -1.884$; $p > 0.05$). On the other hand, there is a significant difference in the present moment between active and inactive quarries, the latter having a lower average value of NDVI ($Z = -9.628$; $p < 0.05$). In active quarries, there is no significant difference between moments ($Z = -1.884$, $p > 0.05$). In inactive quarries, there are significant differences in mean NDVI between moments, with the initial moment having a lower average value for NDVI compared to present moment ($Z = -9.809$, $p < 0.05$) (Table 2, Fig. 3).

Table 2. NDVI average values for active and inactive quarries in initial and present moments

Types of quarries	*Initial moment (mean ± s.e.)*	*Present moment (mean ± s.e.)*
Active quarries	0.246 ± 0.007	0.282 ± 0.010
Inactive quarries	0.268 ± 0.007	0.417 ± 0.008

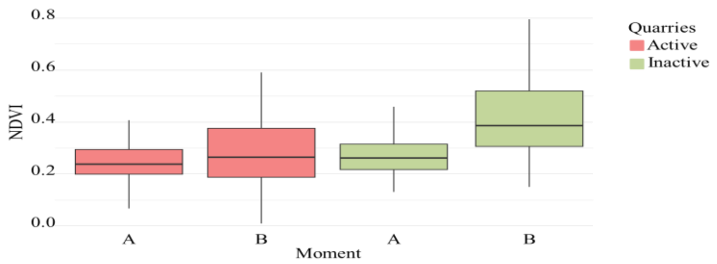

Fig. 3. NDVI differences between active and inactive quarries in initial (A) and present (B) moments

When taking into consideration only surrounding habitat, mean NDVI has no significant differences between forest and open mixed habitats in the initial moment (initial $NDVI_{forest} = 0.274$; initial $NDVI_{open\ mixed} = 0.249$; $Z = -2.312$; $p > 0.05$). In present moment, however, there is a significant difference, with quarries with surrounding habitats covered by forest having a higher average value of NDVI compared to quarries surrounded by open mixed habitats (present $NDVI_{forest} = 0.476$; present $NDVI_{open\ mixed} = 0.315$; $Z = -11.485$; $p < 0.05$) (Table 3, Fig. 4).

Table 3. NDVI average values in quarries based on surrounding habitats in initial and present moments

Surrounding habitats and type of quarries	*Initial moment (mean ± s.e.)*	*Present moment (mean ± s.e.)*
Forest habitats	0.274 ± 0.011	0.476 ± 0.010
Active quarries	0.243 ± 0.013	0.392 ± 0.016
Inactive quarries	0.319 ± 0.014	0.521 ± 0.010
Open mixed habitats	0.248 ± 0.006	0.315 ± 0.007
Active quarries	0.247 ± 0.009	0.233 ± 0.009
Inactive quarries	0.251 ± 0.008	0.366 ± 0.009

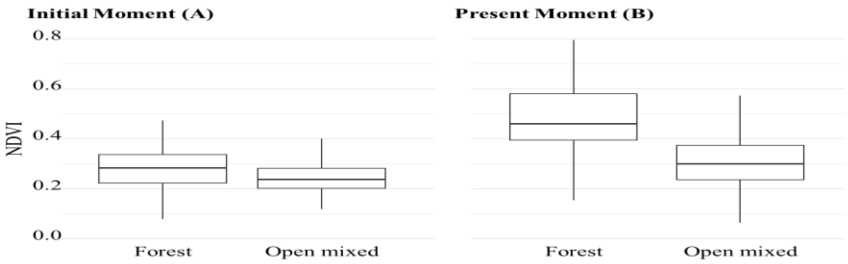

Fig. 4. NDVI differences between quarries surrounded by forest habitat and those surrounded by open mixed habitats in initial and present moments

In quarries surrounded by forest habitats, at the initial moment, NDVI average values are significantly different, with active quarries average values lower than those for inactive quarries ($Z = -3.732$; $p < 0.05$). In present moment, NDVI average values are significantly different, once again active quarries average values being lower than those in inactive quarries ($Z = -6.111$; $p < 0.05$). Just in active quarries surrounded by forest habitats, NDVI average values are significantly different between moments, with lower values in the initial moment compared to present moment ($Z = -5.774$; $p < 0.05$). Just in inactive quarries surrounded by forest habitats, NDVI average values are also significantly different between moments, following the same trend with lower values in the initial moment compared to values in the present moment ($Z = -7.148$; $p < 0.05$) (Table 3, Fig. 5. Top).

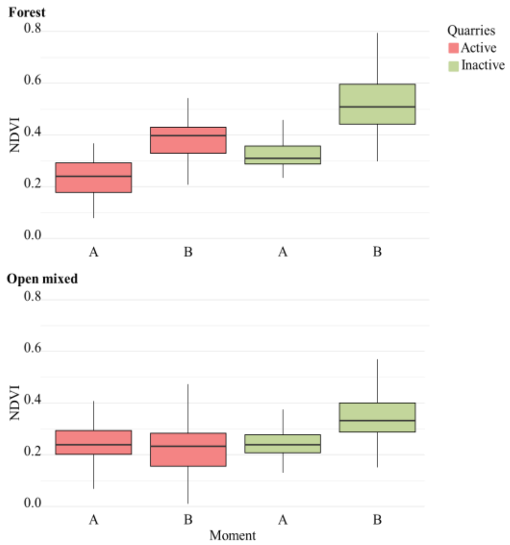

Fig. 5. NDVI differences between active and inactive quarries surrounded by forest habitat (top) or open mixed habitats (bottom) in initial (A) and present (B) moments

In quarries surrounded by open mixed habitats, in the initial moment, NDVI average values are not significantly different between active and inactive quarries ($Z = -0.114$; $p > 0.05$). However, in present moment, NDVI average values are significantly different, with lower values in active quarries compared to inactive ones ($Z = -9.430$; $p < 0.05$). Just in active quarries surrounded by open mixed habitats, NDVI average values are not significantly different ($Z = -1.499$; $p > 0.05$). Just in inactive quarries, there are significant differences, with lower average values of NDVI in the initial moment compared to present moment ($Z = -7.855$; $p < 0.05$) (Table 3, Fig. 5. Bottom).

Correlation analysis shows a low negative correlation between the annual averages of minimum temperatures and NDVI and a low positive correlation between the annual averages of DSR and NDVI in active quarries. Nevertheless, these results showed that minimum temperature explained just 37% of NDVI variation, while DSR explained just 35% of NDVI variation in active quarries (Table 4, Figs. 6–7).

Table 4. Székely-Rizzo-Bakirov Distance Correlation of NDVI and climatic parameters.* = low correlation

NDVI correlation/ Quarries	*Min temp (°C)*	*Mean temp (°C)*	*Max temp (°C)*	*DSR (W/m2)*	*ppt (mm)*
Active	−0.378*	−0.082	0.142	0.355*	0.114
Inactive	−0.118	−0.16	−0.154	−0.292*	0.237*

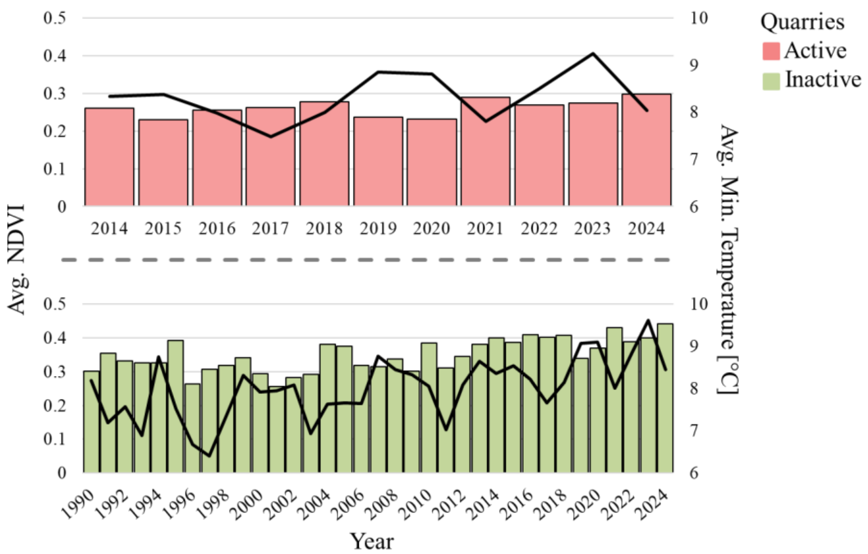

Fig. 6. Annual average NDVI and annual average minimum temperatures over time in active and inactive quarries

Moreover, a low negative correlation was observed between annual averages of DSR and NDVI and a low positive correlation between annual averages of precipitation quantity and NDVI in inactive quarries. However, in this case, DSR explained just 29% and precipitation just 23% of NDVI variation in inactive quarries (Table 4, Figs. 7–8).

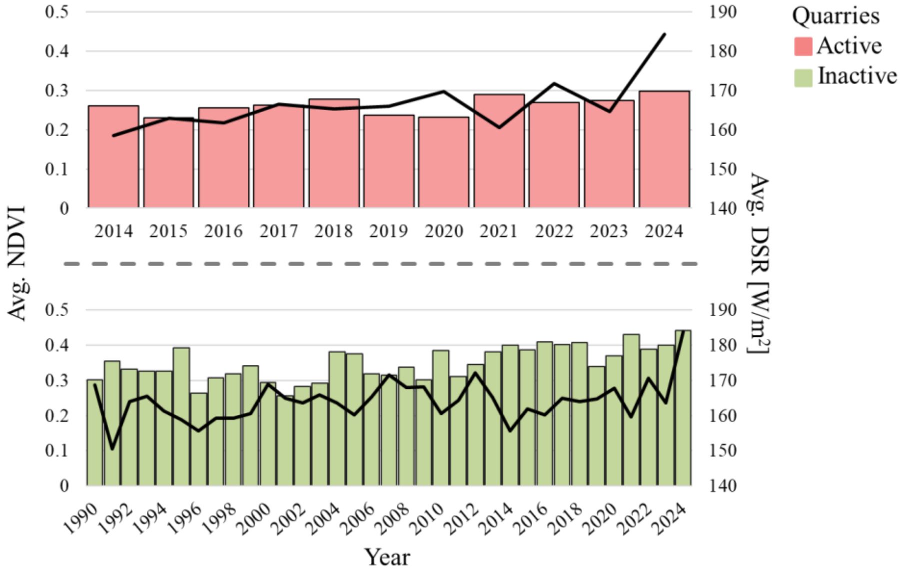

Fig. 7. Annual average NDVI and annual averages of daily solar radiation intensity (DSR) over time in active and inactive quarries

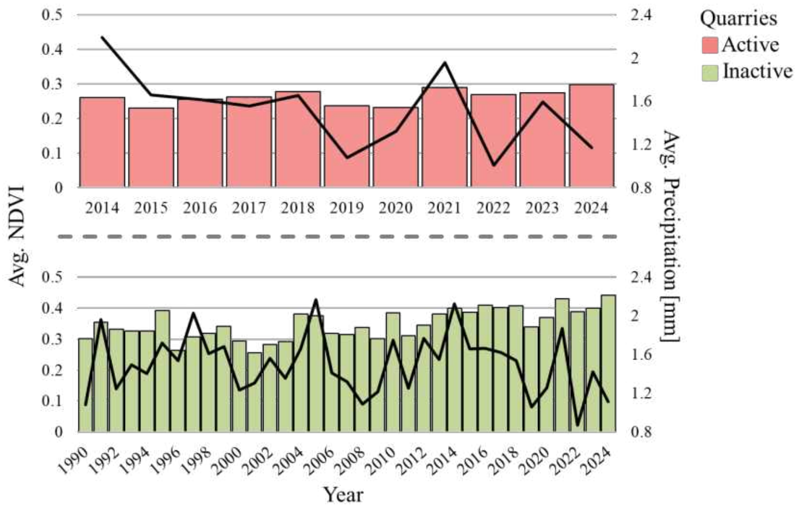

Fig. 8. Annual average of NDVI and annual average precipitation quantity over time in active and inactive quarries

Discussion

Positive NDVI trends have been observed in central, northern and south-eastern Europe,[3, 11]. In Romania, [11] showed an overall positive NDVI trend in southern Romania and Dobrogea region in 1989-2018. Prăvălie et al. [34] also found a nationwide overall increase in NDVI values in Romanian forest areas from 1987–2018, but with a small decreasing NDVI trend in the forest areas from the Extra-Carpathian arc. These negative NDVI trend regions include forested areas in Dobrogea, respectively forested areas from Northern Dobrogea Plateau and from south-western Southern Dobrogea Plateau. [34] Despite a positive NDVI trend on a macro-scale, the aforementioned studies indicate the need for a closer look at NDVI trends at a more regional or even local scale. Our own results for the six chosen quarries from Dobrogea region, Romania, show a general increasing trend in NDVI (Fig. 2), although statistically insignificant for active quarries (Fig. 3). The insignificant positive trend of NDVI values in the active quarries can be attributed to continuous extraction processes, the consequent habitat modification, and presence of workers on site. In inactive quarries, on the other hand, the undisturbed new habitats can be spontaneously renatured either from seed banks in the substrate, anemochory or zoochory. Such new habitats can be beneficial for numerous animal species, hence even promoting seed dispersal by animals [38]. Pignataro, 1999, as cited by Cutaia et al. [8], mentions that spontaneous restoration of limestone quarries in particular is generally achieved in many decades. The three inactive quarries included in our study, which show a clear significant positive trend of NDVI, have been used for diatomite, granite, and, respectively, limestone extraction. Our data extend to almost three decades, since the quarries have been inactivated and might only show an intermediary image of the natural trend of renaturation.

Natural succession restoration processes can have different results depending on multiple factors such as previous land disturbance intensity, species availability from nearby habitats or performance of available species pool [31, 33]. Our results indicate that quarries surrounded by forest have significantly higher NDVI values compared to quarries surrounded by agricultural and steppe habitats (Fig. 4). When looking only at quarries surrounded by forests, we found a significant increase of NDVI over time in both active and inactive quarries (Fig. 5. Top). We hypothesise this is due to a better availability of nutrients and moisture in forest ecosystems, which help with faster establishment of woody species [33]. In open mixed habitats, we found a significant increase in NDVI over time only in inactive quarries (Fig. 5. Bottom). As Prach et al. [33] mentioned, heavily altered sites surrounded by arable or intensely used habitats (such as grazed steppe) would be first conquered by ruderal species, which can be hard to outcompete, postponing advancements in succession stages. Of course, in

this case, only three decades of natural vegetation succession might not be sufficient. We stress the need for further monitoring as well as including more quarries from different microclimate regions.

NDVI and temperature are usually strongly correlated. As such, temperatures rising across Romania suggest that this climatic factor is a good way to explain the mostly positive trends of NDVI seen in studies over the past 30 years [34]. In our case, we found low significance (both positive and negative) for the temperature–NDVI correlations. We assumed that these results are explained by (1) the small size of the analysed areas and limited number of landscapes compared to results found by Prăvălie et al. [34] and (2) different microclimates of a certain area. Gutierrez-Cori et al. [15] also found a negative low correlation between annual average values of DSR and NDVI, but a positive low correlation between annual average values of precipitation and NDVI. During the wet season, for instance, DSR showed a positive correlation with the NDVI, suggesting that during a dry period, vegetation is more dependent on water availability and less on solar radiation [15]. The analyses translate the law of minimum stated by Leibig in 1840 [27] and, on the same trend, we found positive correlation in both active (insignificant correlation) and inactive quarries (low correlation) for precipitations, which is in alignment with the dry climate of the studied region. Moreover, because of the ongoing extraction in active quarries, water resources are supplemented by industry personnel (water used to spray the quarry area to avoid entraining dust particles into the air). In this case, we can state that this activity provides necessary water supply and results in a dependence for solar radiation, resulting in low correlation between NDVI and annual precipitation. In inactive quarries from this dry climate, solar radiation is negatively correlated, and rising precipitation quantities result in higher values of NDVI.

Foremost, our study puts emphasis on the usefulness of using remote sensing data to analyse and monitor inactive quarries. Such a tool can improve and help environmental agencies and non-governmental organisations when making decisions on how to manage inactive quarries. For example, a low positive variation of NDVI in time must drive a human intervention for a rapid renaturation of a certain area, while a high positive variation of NDVI can lead to wild natural succession in that quarry. This step is fast [44], cost-efficient [24], and requires a minimum of site visits. But this method must be supplemented and correlated with many other environmental parameters, such as geology type [35, 46], pedology characteristics [30], and a combination of historical weather data [17, 21, 50], to obtain a precise description of the area. Nevertheless, much more active and inactive quarries must be analysed in order to obtain more detailed results of NDVI patterns.

In addition, we provide a baseline for further use of remote sensing data in ecological studies and biodiversity management plans, in order to reduce necessary time and cost resources.

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